INFLUENCE OF VARYING SOIL CONDITIONS ON NIGHT-AIR TEMPERATURES.

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SYNOPSIS.

A relation shown to exist between the temperature of the soil and the ensuing minimum temperature of the air immediately above, as affected by the varying conditions of the former—constituent character of the soil, moisture content, and the amount and character of the vegetal cover. Low night-air temperatures in gardens and truck farms may often be prevented in the first place by the selection of soil in which there is a sandy component, as sand and sandy loams are warmer than other soils and give off heat in the nighttime by conduction to the air above, thus diminishing the probability of critical temperatures and the formation of damaging frosts. Secondly, the land in use should be well drained of surplus moisture, as wet soils are invariably cold soils and more susceptible to frost damage. Lastly, any soil, whether it be sand, loam, or clay, is warmer when it is clean and free from weeds and unnecessary vegetation, as bare soils are productive of higher night-air temperatures than those covered with a rank growth, from which the heat received in the daytime is lost at night by radiation to space.

Finally, there may be several reasons why frost forms on one side of a street and not on the other, or in one section of a level farm and not in another. If there are contrasting soils, one producing relatively high night-air minima and the other relatively low readings, or if the land differs even slightly in the amount of moisture, or in the kind and extent of the surface covering, or amount of insolation received, frost will appear in the sections which have wet, cold soils, covered with heavy vegetation or uncultivated, while, on the same night and under the same meteorological conditions, frost may not form on other ground close by where the soil is relatively dry, warm, and clean.

It is well known that in mountainous or hilly sections on clear, cool nights frost often forms on valley floors, but not on slopes higher up. This condition has been discussed extensively in meteorological literature and will not be given attention in this article. Rather the subject of differing night-air temperatures on *level ground* will be considered here. On two adjoining farms, and even in different portions of the same farm, practically level, widely differing night temperatures may be observed, resulting sometimes in a killing frost in one place and favorable temperature in the other; not because of any difference in topography, but because of the differences in the character of the soil and extent and condition of its covering.

Remarkable variations in temperature were noted by Prof. H. J. Cox [1] in the Wisconsin cranberry marshes during an investigation conducted there in the seasons of 1906–7; and, as the bogs where the observations were made are absolutely level, the results of this study may be applied to ordinary level farm land. The differences in temperature noted in the Wisconsin investigation were found to be largely due to the variation of the temperature of the soil as determined by the varying conditions with respect to the kind of soil, its moisture, and the amount and character of its vegetal cover. Concerning these variations Professor Cox says:

> On any clear, cool night the cold air overspreads the bog, and here and there are found warm places and cold places and others having intermediate values, depending upon the character of the soil and its covering. It is as if heaters of varying power were scattered over the bog, giving off heat to the air immediately above, some in greater quantities and others in less.

The following condensed table from Bulletin T strikingly bears out the above statement, and shows the average variation in temperature as registered by thermometers placed at the surface of the ground and at a depth of 3 inches at four locations in the Appleton Marsh at Mather, Wis., during the crop season of 1907, these exposures representing various conditions of soil and vegetal cover found in the marshes:

	Station—			
	No. 1.	No. 2.	No. 3.	No. 4.
	° F.	° F.	° F.	° F.
Soil temperature, 6 p. m., 3-inch depth	62.6	58.0	56.6	57.2
Soil temperature, 7 a. m., 3-inch depth	54.4	54.9	55.1	54.9
Loss of temperature by soil during night	8.2	3.1	1.5	2.3
Exposed minimum at surface of ground during night	45.5	43.0	41.7	42.3

Station No. 1.—Peat soil with sanded surface; vegetation thin.
Station No. 2.—Peat soil with sanded surface; vegetation heavy.
Station No. 3.—Peat with moss; vegetation heavy.
Station No. 4.—Peat soil, sanded, with 1 inch of new peat on surface; vegetation heavy.

It is the practice in the more modern cranberry marshes to place a layer of sand 2 or 3 inches in thickness over the peat soil in order to reduce the amount of moisture in the surface soil and to prevent to a certain extent rank growth of vegetation. Unless resanding is resorted to every year or two a layer of new peat from decaying vegetation forms over the sanded surface.

The 6 p. m. soil temperature readings shown in the above table naturally bear some relation to the amount of heat received in the daytime by the soil at the 3-inch depth, the more heat received the higher the reading. Similarly, the 7 a. m. soil temperatures bear a relation to the amount of heat lost by conduction and radiation from the soil, and the differences between the 6 p. m. and the 7 a. m. readings may indicate the amount of heat lost during the nighttime. Where the soil conditions are favorable for storing up heat during the daytime and giving it off during the nighttime to the air immediately above, as at Station No. 1, there is found a "heater" of considerable strength. On the other hand, at Station No. 3, with much different conditions, the character of the soil and its covering does not permit much heating during the daytime and consequently there is little heat to give off at night. There we may say is located a "heater" of low power. The higher average minima of 45.5° at the surface of Station No. 1 compared with the relatively low average of 41.7° at the similar location at Station No. 3 show the remarkable effect of the soil and vegetal cover upon night-air temperatures immediately above the surface of the ground. The readings at Stations No. 2 and No. 4 show results intermediate in value between the extremes at Stations No. 1 and No. 3, depending upon whether the conditions of soil and cover lead to relatively high or low afternoon soil temperatures and later correspondingly high or low night-air minima.

The degree of fall in air temperature during the night depends largely upon the warmth of the soil. Where the amount of heat absorbed during the day is slight and the ensuing night calm and clear, thus permitting rapid cooling by radiation, the result is a low night-air temperature. On the other hand, where a large amount of heat is absorbed during the day by the soil, there can be more heat lost from the soil to the air above before a critical temperature is reached, simply because there is a greater amount of stored heat to draw upon. Although these conclusions are based upon observations made over

[1] Cox, H. J.: Frost and Temperature Conditions in the Cranberry Marshes of Wisconsin, *Bulletin T*, U. S. Weather Bureau, 1910.

marsh land, they may apply with equal force to conditions which are frequently found over level farm land.

Franklin's[2] observations made in 1918–19 in England, covering temperatures taken at the surface of the soil and at a 4-inch depth, "uphold," he says, in referring to Cox's investigation in the Wisconsin marshes, "the view that the temperature and conductivity of the soil play a most important part in determining the minimum temperature at night."

It is now a generally accepted fact that the character and temperature of the soil do affect to a marked degree night-air temperatures up to a height of several inches above the surface, and this influence should not be overlooked in connection with the occurrence of frost on level ground where truck is raised or where berries are grown on vines or small bushes. Of course, on very still nights, at a distance of several feet above the ground, the influence of soil conditions is lost or nearly lost, and it is therefore not a factor in the discussion of methods of protection from frosts in orchards, except for small fruits.

The writer, who was privileged to take part in the Wisconsin research, believes that the knowledge of the relation of soil conditions gained in that study to air temperatures immediately above, might well be applied to general farm land. Moreover, it is hoped to meet the statement so often made that frost is observed on one side of the street and not on the other *without any apparent reason*. The results of the investigation in the cranberry marshes were most beneficial, and the methods now practiced by the growers to avoid damage from frost—sanding, draining, and cultivating—will be discussed in order in connection with their value as an aid in warding off frost where truck or fruit grow near the ground.

ADVANTAGES OF SANDY SOILS.

Sanding, as previously stated, is resorted to in some localities in the laying out of the more modern cranberry marshes in order to reduce rank vegetable growth and surface moisture, and thus prevent low night-air minima. Of course, it is impracticable to sand large or even small areas of ordinary farm land for the purpose of warding off frost, but it is nevertheless well to point out the advantages of sandy soils, so far as heat conservation is concerned, in order that these facts may be of assistance in the selection of ground for the growing of truck and small fruits.

Sand is formed from the disintegration of rock and consists of relatively coarse rock particles. Clay is also formed from the disintegration of rock and differs from sand in that it contains the largest proportion of fine particles of any soil, while sand contains relatively large particles. Loams, strictly speaking, consist of earthy matter composed largely of either sand or clay, but having enough of the former to counteract the cohering property of the latter, and contain particles intermediate in size between those of sand and clay. They also include a considerable amount of decayed organic matter, pure black loam having a larger proportion of decayed vegetation than either sandy loam or clay loam, and it is therefore a poorer conductor of heat. Peat is a carbonaceous matter formed by the partial decomposition of plants in water, and is, of course, also a poor conductor of heat, much poorer than loam even.

Of the soils mentioned, peat is probably the best radiator and sand the poorest, with loams and clays occupying intermediate positions. Pure black loam, however, is undoubtedly as good a radiator as peat. Sand gives out heat slowly, and cools mainly by conduction to the air immediately above, instead of by radiation through the air as do loam and peat. Night-air temperatures over sand and soils mixed with sand are therefore relatively high.

Black soils, of course, are excellent absorbers of heat, and peat, black loam, clay, clay loams, sandy loams, and sand rank in the order named in their absorptive power. A black loam is colder than a sandy loam, however, because, although more heat is absorbed during a sunshiny day, the degree of conduction into the soil and consequent storing up is not so great and more is lost at night by radiation.

Prof. W. J. Humphreys[3] says:

> The better the absorber, other things being equal, the warmer it gets during insolation and the more it heats the air, while the better the radiator it is, the colder, as a rule, it and the air adjacent become during the night. When the atmosphere is clear and dry, and therefore diathermanous, the cooling of objects and their liability to frost depend largely upon their capacity to radiate at ordinary temperatures. A good radiator under these conditions loses heat partly by radiation through the atmosphere to space. It cools rapidly, but the heat it gives off does not all go to warming the air, for a part of it is directly lost to space. On the other hand, an object that radiates poorly gives off its heat in a large measure by conduction to the atmosphere. It tends to conserve both its own temperature and that of the surrounding air and thereby diminishes the probability of frost.

Since one of the chief factors in influencing the temperature of a soil is its capacity for water and as sand retains only a small proportion of moisture when all the free water has been allowed to drain away, it should be apparent that soils having a sandy component, and therefore relatively free from excess moisture, are productive of higher night-air temperatures than those containing more moisture. Sand because of its low capillarity prevents water in the ground from coming to the surface. It also warms easily because of its low specific heat. As a result of these characteristics sand conserves both its own temperature and that of the surrounding atmosphere, thereby diminishing the probability of frost. It is for these reasons in addition to ease of cultivation and quick drainage that truck growers prefer a sandy soil—either sand or sandy loam—especially for early garden crops.

It should be stated, however, that, while a sandy component in a soil is instrumental in modifying low night-air temperatures, this influence is of little consequence after frost has once entered it. This fact was quite apparent as a result of the Wisconsin study, inasmuch as the differences between the exposed minima over sand and peat were small during the month of October as compared with those in the warmer months.

Professor Cox found in the cranberry research that for the two months of August and September, 1906, the average minima 5 inches above the surface of sanded portions of the Appleton and Fitch marshes were, respectively, 4.4° and 5.4° higher than the minima at similar exposures over peat, some daily differences between these locations being as great as 19°.

Other investigators, also, in soil temperature have found sandy soils to be much warmer than other soils. King[4] compared the temperature of a well-drained sandy loam with that of a black marsh soil and found that the former averaged for five consecutive nights 7.5° warmer than the latter, this difference being sufficient to have a most decided effect upon crops.

[2] Franklin, Capt. T. Bedford: The Cooling of the Soil at Night with Special Reference to Late Spring Frosts (II), Proceedings of the Royal Society of Edinburgh, session 1919–20, Vol. XL, Part I (No. 2).

[3] Humphreys, W. J.: Bulletin of the Mount Weather Observatory, Vol. II, part 3.

[4] King, F. H.: The Soil.

O. G. Malde, for many years in charge of the branch experiment station in the cranberry bogs at Cranmoor, Wis., in an unpublished article, writes as follows:

Temperature data recently compiled as a summary of 11 seasons of observations at the Cranberry Experiment Station (1906 to 1916, inclusive) show that there is an average of 58 days between the last spring and the first fall frost (June 25 to August 22) over unsanded bogs, as against 118 days between last spring and first fall frost over sanded bogs. This represents a gain of 95 per cent in length of frost-free season on sanded bogs over that on unsanded bogs. The item of sanding, therefore, greatly reduces frost hazards and conserves the water supply by eliminating the need for frequent flooding to protect against summer frosts. Sanding also permits, and, in fact, requires, deeper and better drainage, and is an insurance against fires on bogs in dry seasons.

The soil in many orchard regions is of sand, as in western lower Michigan, and fruit may be raised on such a soil to advantage. Along the Atlantic coast, Norfolk sand is considered one of the best soils for the growing of truck, while the sandy loam found in many agricultural regions shows the advantages of the sandy component. The volcanic ash of the far West has some qualities similar to sand so far as its heating property is concerned.

When the statement is made that frost without apparent reason is noted in one section of a level farm and not in another, it is now seen that there is a reason and that it may be a question of character of soil, sand and loams with a sandy component being productive of higher night-air minima than black loams, clay loams, and clay.

DRAINING.

Frost occurs more frequently on wet or damp ground than on dry ground, and this is true irrespective of the character of the soil. In the Wisconsin investigation it was found that for the month of September, 1906, in the Fitch Marsh near Berlin there was an average difference of 2.4° between the minima at the surfaces of wet sand and dry sand in locations only 50 feet apart, the soils otherwise being the same so far as vegetal cover was concerned. The average minimum over the dry surface was, of course, the higher. This average included all nights, whether clear, cloudy, or rainy, and the difference was naturally most marked on clear nights; on one such night the thermometer over the dry surface registered 35.8° and over the wet 27.3°—a most remarkable variation of 8.5°, with safety at one point and damaging frost at the other. Since these two surfaces were located in the same section of the bog, distant from each other not more than 50 feet, and there was no difference in the character of the soil cover, as stated previously, the larger amount of moisture present was solely responsible for the relatively low value over the wet surface. The amount of this variation represents roughly the margin of safety which may be assumed to obtain on radiation nights between dry and wet sanded surfaces; but the differences would probably not be so great over loams or clays, as the range in surface temperature over sand is large owing to its low specific heat.

Gardens, fields, and farms well drained are less susceptible to frost than lands poorly drained and having a surplus of moisture, other conditions being equal, as a dry soil is productive of higher night temperatures. This is because part of the sun's heat is used in evaporating moisture from a wet surface and raising the temperature of the water in the soil, while the same amount of heat in falling upon a dry surface more directly affects the soil. Five times as many heat units are required to raise the temperature of 100 pounds of water 1° F. as are required to raise the temperature of a similar amount of dry soil 1° F. Wet soils are always relatively cold because evaporation of their water content keeps their temperature low. This lowering of temperature by evaporation is in proportion to the rate at which evaporation occurs. King [5] shows that the difference in the rate of evaporation from clay and sandy soils when both are well drained is often sufficient to produce a lower minimum by 7° in the clay at a depth of 1 foot. This difference would, of course, be greater at the surface of the two soils, and cause a corresponding difference in the air temperatures immediately above the surfaces. Clay soils are relatively cold because of the large amount of evaporation from the surface, the water capacity of clay being about 40 per cent, while some sandy soils and loams that are warmer than clay may have a water capacity as low as 5 per cent. King states that a given amount of sunshine that will heat a certain quantity of water 10° will raise the temperature of an equal amount of dry sand 52° and of clay 44°. A well-drained soil is not only generally warmer than a damp soil but it is easier to work, and the number of days that it can be worked is also much greater.

In the cranberry marshes ditches, run at frequent intervals, serve to carry away surface moisture and reduce evaporation; and ditching and tiling are resorted to in the draining of truck lands.

Here we find another reason to account for the appearance of frost on certain portions of level land and not on adjoining sections—that of drainage, a deposit of frost being more likely to form where the soil is moist, because such soil is likely to be relatively cold than where it is drier.

CULTIVATING.

In the Wisconsin research it was also found that vegetation, as well as the character of the soil and its moisture, is a most important factor in affecting night-air minima immediately above the surface of the ground. Where there is dense vegetation the soil temperature is kept from reaching a high point in the daytime, since the surface of the ground is then screened from the sun's rays; and, inasmuch as leaves and grasses are excellent radiators and lose heat rapidly, especially when the atmosphere is diathermanous, crops with heavy foliage are more subject to damage from frost than those with thin foliage, other considerations being the same. In dense vegetation and weeds, then, are found high day and low night temperatures.

Now, on the other hand, relatively low temperatures during the daytime and relatively high temperatures at night are found in the air immediately above a bare, clean soil or even one thinly covered with vegetation. The direct insolation is chiefly absorbed by the clean soil and conserved, and given off to the air above at night, largely by conduction, if the soil be sandy, thereby preventing frosts and low minima. But whether the soil be sand or loam or clay, the cleaner it is the warmer it becomes through insolation and the higher are the night-air temperatures above.

The above statements are in harmony with the values contained in the table below, showing the average maximum and minimum temperatures at the surface of the marsh for the crop period from May to September, inclusive, 1907, at the Appleton Marsh, Mather, Wis., at the two stations having contrasting conditions as regards

[5] King, F. H.: Irrigation and Drainage.

covering, but similar environment as regards soil and moisture.

	Station—	
	No. 1.	No. 2.
	° F.	° F.
Average maximum temperature at surface in open	89.1	96.6
Excess at No. 2	....	7.5
Average minimum temperature at surface in open	48.8	46.1
Excess at No. 1	2.7	....

Station No. 1.—Peat soil with sanded surface; vegetation thin.
Station No. 2.—Peat soil with sanded surface; vegetation heavy.

The above data, of course, represent average values, including cloudy weather as well as clear, but it is during clear weather naturally, when critical temperatures are most likely, that the advantage of bare soil over dense growth is most apparent in the resulting temperature conditions. In several instances during the cranberry marsh research the maxima in dense vegetation under the most favorable conditions exceeded that over bare soil by from 10° to 15°, the minima the following morning in the rank growth being from 5° to 8° lower.

PREDICTING MINIMUM TEMPERATURES IN THE VICINITY OF WALLA WALLA, WASH.

By Charles C. Garrett, Meteorologist.

[Weather Bureau, Walla Walla, Wash., August 14, 1922.]

Beginning with the spring frost season of 1915, a localized frost-warning service has been maintained at the Weather Bureau office at Walla Walla, Wash., for the benefit of orchardists and truck gardeners in various districts of southeastern Washington and northeastern Oregon. At one time the district included orchard sections as far away as the Umatilla irrigation project, near the junction of the Umatilla and Columbia Rivers in Oregon, and the White Bluffs project, on the west bank of the Columbia north of the mouth of the Snake River, but the area has been diminished considerably in the last two or three seasons.

As is the case in all of the commercial fruit-growing regions, the extent of orchard-heating operations for the purpose of combating frost is largely dependent upon local economic conditions, and interest in the matter increases and diminishes following seasons with greater or less frost damage.

The cost of installing orchard-heating equipment and the cost of fuel-oil and extra labor of filling and lighting the containers add materially to the running expenses of an orchard. If the prices received by the growers for their products are low, many do not consider that it pays to go to the extra expense of equipping their orchards with frost-fighting devices. Particularly is this true in a region similar to the Walla Walla Valley, which is usually quite free from severe frost damage. In the last two or three seasons heating has been confined mostly to prune and a few peach and cherry orchards. Practically no effort is now made to heat the large commercial apple orchards anywhere in the district. The question as to the effectiveness of orchard heating, when properly carried on, is not now often raised in this district, as it has been quite conclusively demonstrated by a number of prominent orchardists that the temperature within a heated orchard can be raised several degrees above that on the outside. The only question is that of the desirability of going to the extra trouble and expense.

Even though the number of orchardists in the Walla Walla district who are prepared to smudge or heat their orchards is relatively small, a considerable demand exists each season for accurate forecasts of minimum temperatures on critical nights for the fruit. A forecast merely of light, heavy, or killing frost, while of value, is not sufficient.

In addition to a careful study of the morning and evening weather charts, the methods of forecasting minimum temperatures are based primarily on readings of a maximum thermometer and readings of dry and wet bulb thermometers taken, preferably, in the early evening. The instruments should be exposed in a ground shelter under conditions approaching as closely as possible those existing in the orchards.

Studies of different methods have been made by a number of investigators, and explanations published in various numbers of the Monthly Weather Review,[1] and in Monthly Weather Review Supplement No. 16.

(*Method A*) *Dewpoint-relative-humidity charts.*—This method is based on the well-known relationship between evening hygrometric data and ensuing morning minimum temperature. On a comparatively calm, clear night a knowledge of the value of the evening dewpoint enables one to approximate the minimum temperature of the following morning provided the relative humidity is taken into consideration along with the dewpoint. The depression of the minimum temperature below the evening dewpoint is greater when the moisture content of the air is low than in the case where there is a greater supply of moisture. If the relative humidity is comparatively low the dewpoint will be reached later in the night, if reached at all, than if the relative humidity is high. To best utilize the observations of dewpoint and relative humidity in the practical work of forecasting minimum temperatures it has been found convenient to chart the observations on cross-section paper. The relative humidity data are indicated at the bottom of the chart, while figures at the left indicate the differences between the dewpoint at the evening observation and the minimum temperature of the following morning. A dot is entered on the diagram to agree with the observed relative humidity and the variation of the minimum from the dewpoint temperature.

Dot charts have been prepared at the Walla Walla station, one for the first and one for the last half of the spring-frost season. Data for all the clear and mostly clear nights for several seasons were used—a period long enough to afford a fair test of the practical value of the method. On the Walla Walla charts the dots arranged themselves in the form of a parabolic curve. The curve of nearest fit through the dots was calculated by the "star point method." A full explanation of the process employed for calculating the curve is given by Prof. J. Warren Smith in Monthly Weather Review Supplement No. 16. Where many observations are available for making the dot charts the line or curve of nearest fit may be drawn with fairly good results free-hand instead of making use of a mathematical calculation.

By the use of the charts the forecaster, knowing the evening relative humidity and dewpoint at his station, can arrive at a close estimate of the probable minimum temperature at the "key station" on the following

[1] Mo. Weather Rev., October, 1914; August, 1917; May, 1918.